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PRESSURE DIE-CASTINGS

Paper presented to the Institution, Manchester Section, by A. H. Mundey.

AS a metallurgist, I mention first the alloys which are regularly used in the die-casting industry. On special occasions others are made up if some particular property be desired. The six main classes are as follows :—

(1) *Tin-base alloys.* A typical composition is tin 90%, copper 5%, antimony 5%.

(2) *Lead-base a loys.* A typical composition is lead 85%, antimony 10%, tin 5%.

Under the two foregoing classes it should be noted that practically any standard tin-base or lead-base alloys used for bearings or similar work or type metal can be die-cast.

(3) *Zince-base alloys.* Three similar compositions are used, all containing 4.1% aluminium, but with copper content varying from 0 to 2.7%.

(4) *Aluminium-base alloys.* Practically every aluminium alloy which is sand-cast, may also be die-cast. This applies to alloys in which aluminium is the main constituent. It had been stated with much truth, that if a casting cannot be produced in aluminium silicon alloy, it cannot be cast at all (in alluminium alloys).

(5) *Brass,* based on 60% copper, 40% zinc ; brass of the 70% copper, 30% zinc series, is not a practicable proposition in ordinary circumstances.

(6) *Aluminium-bronze,* based upon 90% copper, 10% aluminium. Pressure casting in this series is not without difficulty.

In choosing a suitable alloy, three factors have to be observed : (1) Raw material cost ; (2) Physical properties of the alloy, making it suitable for the particular job ; (3) Suitability of the alloy for the die-casting process.

Although cost of raw material is of some importance, the main consideration should be the cost of the finished die-casting in relation to its serviceability. Thus you may buy iron foundry castings at about three pence per pound, and zinc base castings will cost from seven pence to one shilling per lb., but in the latter case most of or

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all machining operations are dispensed with, usually the zinc base die-casting is stronger than if of cast iron and thickness can be materially reduced.

There are many perfectly serviceable zinc base die-castings which weigh only half that of the iron castings replaced. But die-castings are not bought and sold at per lb. and it may be possible to replace the iron castings by aluminium base alloys.

Other considerations in choice of alloy include—the character and amount of stress the casting must stand, usually a die-casting is stronger than the same alloy in the sand cast condition, due to its fine grain and relative freedom from porosity. If shock loading or repeated stresses of several tons per sq. in. be expected, aluminium bronze may be well advised, although both zinc base and aluminium base alloys have made some notable records. Zinc base alloys should not be used in presence of acids, or aluminium with strongly alkaline solution, both are satisfactory when in contact with soapy water or oil. Soldering of zinc base or aluminium base die-castings presents some difficulty, although with special compounds and skilled technique this may be overcome, but it is better to avoid this in designing if possible and it generally is so.

If a special finish is to be applied, the fact must be borne in mind in choosing the alloy, for varying treatment may be required, which will be noted more fully later. Another factor to be observed in choosing an alloy, is its effect upon the die; for instance if pure zinc alone were used the steel die would be quickly galvanized, but if 4% of aluminium be present this danger is eliminated. The alloy must not be hot short or it will crack before it can be removed from the die. A 70% copper and 30% zinc brass is very weak just below its melting point and die-casting with this alloy is very troublesome, on the other hand the 60/40 group die-casts well. The melting point must be as low as reasonably possible having in mind the conditions and character of the casting.

Automobile carburettors of extremely complex design are produced as pressure die-castings in zinc-base alloy with a die life of several hundred thousand shots. If a brass casting were attempted, and it would be most unreasonable, the die would be ruined in about half a dozen shots.

Undoubtedly, the great advance in the quality of zinc-base alloys has been one of the chief factors in the development of the die-casting industry. Everyone consciously, or unconsciously, is a user of die-castings in this alloy. In 1936 about 12,000 tons were consumed in this country and the quantity is rapidly increasing; in the United States about five times as much is used. In the older times the zinc was hardened by the addition of varying proportions of tin, about 3% of copper and about 1% of aluminium. This type

of alloy produced many thousands of beautiful die-castings, with a fine definition and finish, but they could not be relied upon as to permanence. They were apt to " age," becoming brittle and changing in dimension after being in use for some time. Complex form, and abrupt changes in section being particularly susceptible.

We owe a great debt to the New Jersey Zinc Company of America, for its work in the improvement of zinc-base alloys. As the result of the researches of the Company's scientists, tin was altogether eliminated from the alloy and a grade of zinc of the highest quality was introduced to the market. It is of 99.99% purity, the presence of minute traces of tin, lead or cadmium is avoided.

These particular advances occurred between 1929 and 1932 and since then the progress of die-casting has been phenomenal, but not more so than the advance in the physical qualities and the reliability of the zinc base alloys. It was found in relatively early days, that a very small proportion of magnesium is benificial between 0.01 and 0.1%. The usual amount now is 0.03 % ; it greatly assists in making alloy stable.

Table 1 gives the compositions in general use. For hardness and strength 2.7% of copper is used. For ductility or resistance to repeated stresses, copper free-alloy is recommended. A 1% copper content is becoming popular as occupying and intermediate place in regard to physical properties. A slight dimensional change occurs after casting ; all alloys contract slightly over a period of a few weeks, probably 0.003 in. per in. This is not, as a rule, important. But for work in which great accuracy is important, a copper-free alloy should be used and a low temperature annealing employed about three hours at 100°C is sufficient. Low copper content is recommended for castings exposed to prolonged action of steam.

TABLE I.—PHYSICAL PROPERTIES OF THREE ZINC-BASE ALLOYS

		Mazac No. 2 per cent.	Mazac No. 3 per cent.	Mazac No. 5 per cent.
Composition	Aluminium	4.1	4.1	4.1
	Copper	2.7	—	1.0
	Zinc (99.99 purity)	balance	balance	balance
	Magnesium	0.03 (about)	0.03 (about)	0.03 (about).
Tensile strength		19-21 tons sq. in.	15-17 tons sq. in.	18-19 tons sq. in.
Elongation in 2 inches		3-8%	2-5%	3-6%
Brinell Hardness		83	62	73
Impact strength as cast		19 ft./lb.	20 ft./lb.	17 ft./lb.
Impact strength after ten days in steam		1 ft./lb.	22 ft./lb.	11 ft./lb.
Electrical copper conductivity = 100		26%	27.5%	27%
Weight per cubic inch		0.25 lb.	0.24 lb.	0.25 lb.
Melting point		397.3° C.	380.6° C.	380.4° C.

Aluminium alloys are both gravity and pressure die-cast, the former accounting for the larger output. There are several reasons for this. Many designs are not at the moment commercially " pressure die-castable." Pistons, for instance, are so considerably undercut that hand operation has to be employed to manipulate the cores. Crank cases of which wonderful castings are made by Messrs. Leyland, by the gravity method, but machines in this country are not big enough to tackle them for pressure casting. This will probably be remedied in the near future.

To produce really solid aluminium alloy pressure castings, high pressure appears to be essential, under very experienced direction and by skilled operators. It is more difficult to avoid porosity in aluminium base alloys than in zinc base, but with a pressure of from 2 to 3 tons per sq. in., a light alloy pressure casting can be made more solid than a gravity casting.

The advantage of this class of production are obvious ; it is now possible to produce a vast number of articles and details of every-day utility at a cost hitherto impossible. Household articles, too numerous to mention, are now available—vacuum cleaners may be mentioned as a single example. Thus, the industry has promoted its own market which is constantly expanding, particularly as designers are becoming better acquainted with it and consider its possibilities in the first stages of a plan for any new article or component. Pure aluminium can be die-cast, but as it is weak at high temperatures simple forms only can be considered.

The number of alloys proposed and to a large extent used, is probably too great. Silicon, copper, iron, zinc, nickel, or magnesium are added according to the properties desired. The table shows the composition and properties of the principal alloys in use, and which may be considered typical of present day practice. Heat treatment is sometimes employed.

Aluminium-silicon alloy deserves special notice. A foundry casting in a 12 to 13% silicon alloy is weak and brittle. The structure is shown under the microscope to be coarse and laminated, but if it be " modified " by the addition of a very small amount of certain other metals, such as sodium—a method which has been the subject of a number of patents ; the grain of the metal is refined and the strength and ductility greatly increased. In the process of pressure die-casting, the alloy is found to have attained a measure of " modification," even without the addition of any foreign modifying element, but in any case information and facilities for modification can be obtained from the holders of the patents ; a reference to these companies is recommended.

TABLE II.—PROPERTIES OF SOME WELL-KNOWN DIE-CASTING ALUMINIUM ALLOYS

Alloy	Major constituents Balance Aluminium						Mechanical properties in the die-cast form		
	Cu. per-cent.	Si. per-cent.	Zn. per-cent.	Fe. per-cent.	Ni. per-cent.	Mg. per-cent.	Tensile strength tons per sq. in.	Elongation in 2 in.	Brinell Hardness
L.11 ...	7 to 8	—	—	—	—	—	8	3	55 to 60
L.8 ...	12	—	—	—	—	—	9	1 to 2	75 to 80
L.33 ...	—	12	—	—	—	—	12 to 13	8	55 to 65
L.5 ...	3	—	13	—	—	—	11	3	60 to 70
Y alloy L.24 ...	4	—	—	—	2.0	1.5	18 to 20	2	95 to 100
	Usually heat treated after casting.								
Birmabright	—	—	—	—	—	3 to 6	11	5	55
D.T.D.165 ...	—	—	—	—	—	plus 0.25 to 0.35 Mn.			

Brass.

The melting point of 60/40 brass is 920°C ; it is this high temperature which makes for difficulty. The life of the die is seriously shortened and the expense increased, and for the same reason intricate forms and small cored holes are impracticable. Not only are the fine cores and sharp edges eroded or worn away, but the surface of the die becomes roughened into a crazy pattern, thus constant adjustment and renewals become imperative. Despite all this, excellent pressure die-castings are produced in large quantities, but designers and users must keep the difficulties and restrictions in mind. The crazy pattern produced on the surface of the hard steel die is no new phenomenon to the ordnance engineer.

The gun maker is familiar with the necessity for rechambering of artillery pieces, due to the destruction of the surface of the parts which are in immediate contract with high pressures and high temperature of the gases in service. Constant researches by metallurgists in the production and treatment of improved steels have done much, but the troubles have not yet been wholly overcome. In pressure die-casting, the operation is carried out whilst the metal is in the plastic condition, a soft state of about the consistency of whipped cream, that is, at a temperature between those of the solidus and liquidus of the alloy. The most familiar case in everyday metallurgical practice being the condition of plumbers solder whilst the operator is making a wipe joint, or the motor car body builder in the use of filling solder. Zinc oxidation is not serious in these conditions, under high pressures. In the Polak machine a pressure of about 3 tons per sq. in. is used, and to this we owe much of the success which has been attained. The accuracy obtainable in brass pressure castings is from plus or minus 0.005 to 0.007 in. per in.

Although, as has been stated, zinc oxidation is not at the present time found to be a serious handicap, this is largely due to effective mould dressing. A solution containing very finely divided graphite

in suspension or such other chemical inhibitor being used. If the casting be produced from the alloy in actual fluid condition, the life of the die steel is shortened to a serious extent.

For brass pressure die-castings, many die steels have been subjected to prolonged and practical service experiments. The casting temperature is higher than the softening range of most steels, so that a tool steel which is " red-hard " is essential. A composition of carbon 0.3 to 0.4%, tungsten 8.0 to 15.0%, chromium 2.75 to 3.75% is widely used. The mould is cut in the relatively soft state and it is subsequently hardened to about 440 Brinell. The heat treatment is of the greatest importance. Die life varies with size, weight and wall section of the casting 3,000 to 50,000 shots appear to be the general experience. At about 15,000 shots, the surface trouble is apt to become manifest, first in faint haircracks, then advancing to the decided crazy pattern mentioned.

Aluminium Bronze Die-casting.

An alloy of 94% copper and 6% aluminium is as strong as a low carbon steel and decidedly more ductile. With 10% aluminium and 90% copper, the alloy in its die-cast condition is as strong as a medium carbon steel giving about 35 tons per sq. in. tensile strength and and an elongation of 35% in 2 in. With 13% aluminium and 87% copper, it is so brittle as to be useless for all constructional purposes. The metallurgical reasons are very interesting but cannot be considered at this stage.

The alloys of this series are sensitive to heat treatment and certain changes occur in the physical conditions and structure, relative to the speed of solidification and cooling which affect its useful mechanical properties. It will thus be seen that die-casting of these alloys, particularly by pressure methods, are not simple and considerable experience is demanded before a satisfactory technique can be obtained.

An accuracy of plus or minus 0.005 in. per in. can be maintained. Holes of greater than $\frac{3}{16}$ in. diameter can be cast ; a taper of about 0.015 in. per in. is generally allowed. Casting of threads or inclusion of elaborate under-cuts should be avoided if possible.

Additions of iron to the extent of $\frac{1}{2}$ to 2%, displacing a corresponding amount of aluminium, an increase of hardness and strength in the 10% alloy. Manganese and nickel may also be added.

Design of Die-casting and Dies for their Production.

In the majority of cases the reason for the adoption of die-casting into the general scheme of production, is to save money. In order that this may be effected, the design of the particular articles or components must be so arranged that they may be conveniently

cast. The die-casting firms who make a speciality of this method of production take care to retain designers of great skill and experience, who not only design the dies and to some extent machines, but also gladly co-operate with potential customers or clients in the early stages of the conception of the article, in order that difficulties which would otherwise have to be overcome are obviated at the outset. By taking the fullest advantage of this co-operation, maximum output is generally secured and the longest die life possible ensured, thus economy is obtained in all directions.

It would be impossible to give a comprehensive account or instruction in the skilled work of die design, but a few basic principles may be laid down, the application of which must be worked out to suit each particular job, and the innumerable variations provided for as they are found to be necessary. The mould and cores are, in the vast majority of cases, of solid steel, the die must be closed securely for the casting operation and opened for the removal of the casting. The cores must be inserted and extracted in proper sequence, and the careful designer takes care that the extraction shall, as far as possible, be in straight lines, and the directions of movement of the cores shall be as few as possible. A design which hinders rapid operation of the die should be avoided as far as possible. Further, due consideration must be given to the selection of the best places for the runner and the parting line. Dr. Arthur Street has formulated some of the general considerations which will be found necessary to observe.

TABLE III.—GENERAL DESIGN

Shall the part be produced by Pressure Die-casting?		What alloy shall be used?	Can the part be grouped into a Multiple tool?
		Where will the parting be?	
Do any holes or recesses cause the part to be under-cut?			Do any bosses or lettering etc., prevent the die from opening freely?
Will the running of the casting interfere with cored holes?	Taper cored holes	Can cored holes be grouped into fewer directions?	Is the diameter of cored holes suitable?
Is the section correct in order to obtain good surface appearance?		Is the section as uniform as possible?	Will sharp corners have to be filetted?
Are threads required to be cast?		Are inserts to be included?	Is special engraving or lettering required?
Will the die-casting have to be machined?		Is any special finish to be applied?	Will packing include any special problem?

Thus, the die must be capable of forming the casting of the required shape, size, and accuracy. It must permit the free flow of metal into every part through the necessary gates under pressure, and after the removal of cores by suitable mechanism shall permit

the ejection of the casting by means of ejector pins without distortion or other damage. Suitable vents must be provided for the escape of air displaced by the inrush of molten metal. The whole equipment must permit the rapid " stripping " or removal of the casting after solidification.

Many of the very essential requirements to be considered at an early stage of design of casting and die such as venting, position of gate and amount of taper, are decided upon experience. No definite rules can be laid down which will be universally applicable. Provision for the proper placing of inserts must be made.

Every recess in a die-casting must be formed by a core of steel of appropriate shape, which projects into the die cavity whilst the alloy is entering and is withdrawn when the casting is solidified. If the direction of the hole or cavity is parallel with the die movement the core is withdrawn from the casting as the die is opened. If, however, the hole is in any other direction it is necessary to provide separate mechanism to operate the core, generally immediately before the opening of the die. The shape and size of the holes require consideration in design. The lower the melting point of the alloy, the smaller the holes possible for practical purposes.

The position of the holes is important, thus a core placed at right angles to the direction of the incoming metal and near to the runner is apt to give trouble because of the impact of hot metal at high velocity on to the core, which may become gradually eroded. Further, it has to be pulled out of the casting just at the moment when the metal (having only just solidified), is comparatively weak. A rule for permissible tapers is an impossibility but the accompanying table gives approximate figures as a guide.

TABLE IV.—APPROXIMATE TAPER TO BE ALLOWED ON CORED HOLES

Taper per inch of length.

Alloy	In a flimsy Die-casting.		In a sturdy Die-casting	
	Long slender hole.	Short hole.	Long slender hole.	Short hole.
Tin and lead base	0.0005"	nil	0.0005"	nil
Zinc base	0.005"	0.002"	0.002"	0.001"
Aluminium	0.025"	0.02"	0.02"	0.015"
Brass	Do not attempt	0.025"	Do not attempt	0.02"
Bronze Gravity die-cast	Do not attempt	0.02"	Do not attempt	0.015"

Accuracy in cored holes is greater when the cores are included in the main die block. The cores must be well and skilfully finished and correctly heat treated. In casting blind holes, difficulties increase as the cores are supported at one end only. Cores located upon the parting lines should be avoided if possible.

Holes which pass through each other, involve the withdrawal of one core through its fellow in proper order ; if this can be avoided in design it should be ; if unavoidable, the cores must be of different

diameter. The smaller should be withdrawn first of necessity. Complications of this sort are apt to be troublesome and if possible the larger hole should be cored, and the smaller drilled or finished by drilling.

Undercutting in a casting involves the dismantling of a part of the core, in order to permit its withdrawal. This is a longer operation as separate manipulation or mechanism is necessary. It is more common and is easier in gravity die-casting than in pressure work. The case of automobile pistons is a very familiar case. Curved undercuts may be cast by rotating the core about its axis in many cores.

Knock-out centre pieces and dismantling devices are adopted. An assistant to the casting operator is employed to extract the cores and casting from a portion of the die apart from the machine but close along side, three fitments of similar design being generally used to maintain the sequence of operations.

Occasionally a loam or sand core is employed in special cases, but the maintenance of a supply of cores close at hand for use in assembling the die for each cast, and the fragile character of the loam cores and also the additional operation of making a fresh core (and drying it thoroughly) for each cast, combine to make such a handicap that the designer strives to avoid this in usual practice.

Whenever possible, the parting line should be straight, this facilitates the production of a good fit between the faces of the two main portions of the die, and avoids the difficulty caused by irregular or side thrusts when the fluid metal is forced into the mould; weakness in the casting is sometimes caused by this. Exceptions to straight line parting demand very fine work in die making. Venting of the die is usually provided at the parting; the width of the vent usually does not exceed 0.003 in., otherwise fluid metal is forced through the vents. In many cases the space between the faces (although a good fit) permits the ejection of the air; the cores also help in this matter. Skilled and familiar experience guides the die maker in the positioning and number of vents.

Actual design of dies, whether of simple character or complicated by numerous cores and intricate details, provision for several castings in one die, screwed holes or external threading, knurling, the inclusion of inserts and such like details must of necessity depend upon the job to be done. No hard and fast rules can be laid down. Numerous descriptions with illustrations have been given in published articles and treatises. These should be studied closely.

Ejection of the finished casting has not been mentioned; it will be appreciated that frequently this has to be done quickly after solidification, when the casting is in a hot and relatively weak state, suitable ejector pins are provided so as to work in the portion of the

die which contains the casting in such a manner that by manual or automatic action they are advanced, thus pushing out the casting without risk of distortion and at the same time leaving but faint marks upon the finished article.

Die Life.

One is occasionally asked, how long does a die last ? The question cannot be answered directly, so many factors enter into the problems, such as the character of the alloy to be used and directly associated with this the temperature of working, the type of casting, and the degree of accuracy and finish demanded. The material of the die which has already been mentioned, must vary with the duty to be performed. Heat treatment alloy steels are largely used by the leading producers even for zinc-base alloys, whilst aluminium and yellow metal alloys, working at relatively high temperatures, demand alloy-steel dies almost exclusively.

The die steel should be uniform and of high quality, with very low sulphur and phosphorus content. Carbon content should be regular. Usually the die is cut in the soft state and the first samples run off before heat treatment. The die is then dismantled and each component carefully hardened, then reassembled and any distortion removed by " lapping " as may be necessary.

The necessity for special care of core pins has been mentioned and also the occurrence of the surface hair line, or crazy pattern cracks. The form of casting also influences die life, due to the direction of the flow of the fluid metal, and other details which obstruct the free entry of the metal under pressure. Specimens are shown, exemplifying these features. One a comparatively complex casting but straightforward to cast, produced about 250,000 castings, whilst a simpler looking article, which did not admit of easy casting yielded less than 50,000.

Lettering and engraving should always be carefully studied so that the die opens and closes easily, and permits the casting to leave conveniently. It is easier to provide raised letters on a casting than sunken ones. The castings of threads and of gear forms is achieved by the pressure process. Square threads are more troublesome than Whitworth.

Cost of Die-casting.

Die-casters do not estimate at a rate per lb., but at per casting or at per hundred or gross. The reasons are obvious. Part cost of die is generally included in the quotations for a reasonable number

say 10,000, but when the original cost of dies has been partially or wholly paid, there remains many charges for adjustment, renewals, and setting up of machine and dies, when a repeat order arrives. It will be appreciated that a very large proportion of the expense is contained in the design and die-making departments. Quantity enters into the cost very seriously. The die-caster should be given every available scrap of information which the user has in mind, in order that his designer, die-maker, and estimator shall be fully armed.

Plating.

Plating zinc-base die-castings is regarded by many as a difficult operation. It is rather in the nature of a specialists job. The casting should be free from pin holes. Castings from the highest grade zinc and with relatively low copper content are apt to give the best results. Grinding and polishing should not be too drastic, so that as little of the outer skin as possible is removed. Cleaning by a rapid alkaline electrolytic method is good. Thorough rinsing is necessary. Then an acid dip and again a thorough rinse. Copper plating follows. A very light flash coat or a heavy coat is a matter of discussion and judgment. Temperatures of 110 to 180° F. commonly used for copper plating bath. The nickel coating follows. Users sometimes specify the thickness of nickel coating to be applied—usually from 0.0005 in. to .00075 in. It would be idle for me to attempt to discuss the details of nickel or of chromium plating processes. Usually chromium plating of 0.00002 in. to 0.00003 in. is employed.

Plastics.

The employment of plastics as competitors cannot be expected readily to find favour with a metallurgist, but the craft has been so successful, and further it can be employed in conjunction with metal die-casting work that one may be pardoned for introducing it.

The moulded products are substances which, under the influence of heat and pressure, become plastic, so that they may be moulded in dies to form solid articles. They may be divided into two main classes—"thermo-setting" and "thermo-plastic." Bakelite is the best known of the thermo-setting; it is composed of phenol formaldehyde. Another is "urea formaldehyde." The latter is called "Beetle"; it is clear coloured and can produce translucent glass-like mouldings and can be made to take light tints. The material is usually blended with a filler such as wood flour, and when moulded, the finished product gives about 2 to 5 tons per sq. in. tensile strength.

Thermo-plastic compounds. Cellulose acetate is the principal material used in this group. (Glass is, of course, a member of the group). The material is used first as a powder fed into a hopper

which is electrically heated to a temperature of from 140° to 160° C., and then extruded through a small orifice by pressure into a mould somewhat similar in principle to die-casting. The thermo-setting compounds change in constitution under the influence of heat and pressure, and scrap so treated cannot be used again. Thermo-plastic compounds can be used again as in the case of metallic alloys. Metal die-castings are sometimes coated with thermo-plastic compounds, and acquire a pleasing finish.

Chemical finishes, both inorganic and organic, are applied to die-castings, but as this address is becoming of an inordinate length, I must refer my audience to the excellent little article by Dr. Street, for an informative summary of these.

Discussion

MR. F. A. PUCKNELL (Section President, in the Chair) : In the most interesting paper to which we have listened very considerable information has been given on not only the method of producing pressure die-castings and the selection of the correct base for various functions but also the duty of the designer in taking advantage of the weight and cost reductions possible from the use of die-castings by giving due consideration in the initial stages of designing to the incorporation of such parts with consequent savings in manufacturing costs. The clean and pleasing appearance, strength and fine tolerances with which pressure die-castings can be produced should be carefully noted by designers and production engineers so that when quantity requirements economically permit, use should be made of them to the exclusion of other forms of materials not having such points of appeal. I am certain that in general engineering practice the field of application for die-castings has not been anything like sufficiently surveyed and that in many cases it would repay handsomely the full-time attention of a cost reduction engineer. I would enquire of the lecturer whether the application of a hard chromium surface to the dies has the effect of improving the resulting surface of the casting and lengthening the life of the die and whether this is standard practice ?

MR. MUNDEY : It has been suggested and tried a number of times to coat the surface of the dies with chromium in order to give a fine surface and I believe it is done very largely for certain jobs. Whilst we all know that chromium is very hard indeed, I cannot imagine chromium plating standing the wear that Mr. Vance and I have been discussing. Chromium plating under the microscope is proved to be very porous and will begin to flake and peel when a temperature of 1,000° is reached.

MR. VANCE : It has been of great interest to me to listen to a paper which has covered so much ground. Mr. Mundy mentions 2 to 3 tons pressure per sq. in. on the Reid-Prentice Machine and I wonder what pressure he would recommend on the Maddison Kipp Machine, as we use 500 pounds per sq. in. He stated that the die makers have trouble with the steel. We had a die which only gave us 2,000 shots ; we sent to Krupps, Germany, who made a die for us which gave us only 4,000 shots. We then sent to an English firm, Samuel Osborne, who gave us a die of nikel chrome molybdenum and we have had 80,000 shots from this and it is still good to-day. I am wondering whether nickel chrome molybdenum solves your difficulties.

MR. MUNDEY : I am sorry I have not got a slide of the Maddison Kipp Machine, but I have a large diagram and if any gentleman would like to see it afterwards, I shall be pleased to show it to him.

I do not think I said that 2 to 3 tons was necessary ; I do think, it is desirable. I know it has been taken up a good many times with well-known designers. We have had such wonderful experiences with high pressure machines : as I have mentioned, Reid-Prentice claim much higher results. If you can get 500 lb. with air pressure I am sure Mr. Vance and the users of the Maddison Kipp Machines are very fortunate. With regard to the closing up of the nozzle, I have had a great deal to do with Reid-Prentice Machines, probably more than any metallurgist in this country, and I find when the metal is squirted through the nozzles it tends to stop up the mouthpiece. I have been assured before that the Maddison Kipp Machine does not have this trouble. I am glad Mr. Vance has had such good luck with his new die. It is very nice to think that Osborne's could produce such a good job. What material were the castings made of ?

MR. VANCE : Aluminium Silicon.

MR. MUNDEY : Aluminium Silicon gives us no trouble at a temperature of 600°, but we get trouble at 1,000° when there is continued expansion of the very fine top surface : you cannot get the self-same stress continued right through the body of the die. I wish we could overcome this trouble. We have not had any trouble with aluminium, only with brass at the temperature I have mentioned, that is 550°.

MR. JONES : In connection with nitrogen, this is not in actual contact with the metal, but it is purely in the bottle at the front side of the machine, and the rapid expansion of the nitrogen forces the metal into the dies. Nitrogen is used for safety. I shall be glad if the lecturer will inform me, when die-casting brass what is the condition under which the dies are used in the ordinary way. I would like to know what treatment is given to dies, are they water cooled or heated ?

MR. MUNDEY : I quite understand that nitrogen does not come in contact with the metal. Die-casting of brass—you start with the dies warm but the back part of the die should always be cool so that the operator gets forward with his job and does not get too hot, and gradually allows a little water in, if and when required cool. The heat is extracted from the die by cooling the back part of it.

MR. ANGUS-BUTTERWORTH : Is there any machinery for finishing joint marks after the die-casting has been produced ? I recently visited a plastic works where several of the girls were employed in trimming up the product by hand and this seemed a most inefficient way.

MR. MUNDEY : I must confess that all good die-casting shops have very efficient fettling and finishing machines. There are

various small holes and burrs around the edges of a good die-casting so that a very efficient fettling and trimming shop is necessary.

Mr. HUMPHREYS : In regard to the stated tolerances of die-castings, .0005 in. does not sound very good, and I would like to know what kind of accuracy can be expected on flat faces ?

Mr. MUNDEY : You get accurate tolerances particularly on zinc base castings, but not brass. You can also get them on aluminium silicon 13%. We can get down in many cases to .0002, but usually such accuracy is asked for on small work only. Regarding flat faces, I mentioned having had a die casting sent to me after seven years in service. It was one of the old zinc base, hardened with tin and copper, and it had not altered .00001. It was a sliding fit and certainly the designer who asked for it wondered if he was wise in applying for this. Sometimes this can be obtained but you have to pay such a high price it is not worth it. Very high accuracy can be obtained on certain things.

Mr. VINES : I want to ask a similar question to the last speaker in connection with the question of screw threads. Can you die-cast the thread to any particular gauge ?

Mr. MUNDEY : In connection with Mr. Vines' question an elementary example, although very useful, is the making of perambulator hub caps which can be produced to .00001 on the thread diameter, the core being wound out of the die just after solidity. The accuracy on this job is marvellous but, of course, not necessary. However, one has to be careful of the allowance one makes because you may get the screw thread contracting due to solidification on cooling, so that one has to make allowances for this.

Mr. FRANCIS : We have been having a little trouble lately with some round bakelite mouldings which have been coming in oval, due to cooling. Has Mr. Mundey had any similar trouble with pressure die castings ?

Mr. MUNDEY : We do not have much trouble with zinc base casting, but due to the uneven section which would pull it out of shape it is kept in the die just long enough to cool. In the old days castings went out of shape due to crystallization, but this does not apply to present day castings.

Dr. STREET : I really came here to learn and not to speak. However, die-casting is a very fascinating subject and like other fascinating things I could mention, it has its dangers. There are possibly two dangers, the first being it looks so easy, particularly the handling and making of the castings, and it really is not so. Mr. Mundey stresses the difficulties that arise. The second thing is that it looks so easy to make elaborate die-castings that we may be tempted to try it. Not so long ago we were in a works in Paris and we were absolutely amazed at the intricacy of their die-castings ; for example there was one aluminium die-casting with holes $^1/_{16}$ in. diameter and

about 6 in. long. Their trimming shop was about twice the size of the die-casting shop, and we saw a whole staff of women workers trimming out the holes. We came to the conclusion that it is best to be level-headed when using die-castings, particularly with machine tools now having such a pitch of excellence.

Mr. MUNDEY : There are many snags in die-casting, as you can imagine. I have been in the engineering business all my life, and I have never seen anything so fraught with snags as die-casting, and to appreciate this, one has only to go into the drawing office and see the number of little devices that have to be employed to turn out a satisfactory job.

Mr. LLOYD : I appreciate the difficulties to obtain accuracy in die-castings, and I know it all depends on the size of the casting. I would like to know what accuracy can be expected where steel spindles pass through the castings. I would like to raise another point Mr. Mundey has not mentioned, the question of putting inserts into the die-casting and whether it is a sound job on the accuracy of that part. As far as die-castings are concerned I have had a lot to do with them and from my experience a successful and accurate casting is obtained when the material is consistent throughout. Our designers have in the past consulted the die-casting specialists on new designs. I think there is a big field for die-casting which is growing every day.

Mr. MUNDEY : Mr. Lloyd is quite right ; they have been able to make good die-castings, particularly when there has been co-operation between the designer and the die-casting specialist. I do urge that you take the matter up with the die-casting specialist as, although the man may be a skilled designer, he may not have had the opportunity of watching other things in the die-casting practice. With regard to inserts, these are most useful and in very many cases in which inserts are put into the die you can get a high degree of accuracy and dependability. I could not give you a general statement as to the degree of accuracy in all cases, but if Mr. Lloyd continues to permit his designers to co-operate with the die designers and die-casters, he would have many cases in which steel spindles could pass with the greatest of ease through holes which have been die-cast.

WHAT THE ENGINEER SHOULD KNOW ABOUT STEEL

Paper presented to the Institution, Yorkshire and London Sections, by W. H. Hatfield, D.Met., F.R.S.

IT is a great pleasure to me to talk to you on this subject of steel metallury. I understand that I am requested to answer three questions— the first relating to " When should we use alloy steel and when carbon steel ? " ; the second, " What about the question of inclusions ? " ; and the third, " What about grain size ? ". Each of these three questions could well occupy the time at my disposal, but I shall try to touch on all of them and give you a statement on alloy steels from my point of view.

Someone, before the lecture, said that it always appeared to him in his early days to be rather wonderful that the addition of 0.1% of carbon to iron should produce a metal of such widely different properties from the pure iron, and, indeed, it is wonderful. When you think of it, the carbon which is added to the steel in the liquid form is precipitated in the solid as iron carbide, which is really, for the purpose of my argument, a non-metallic substance of a very hard and brittle nature. If you look down the microscope at a piece of steel containing 0.1% of carbon, all you will see is a very soft ductile crystal aggregate of pure iron with this hard brittle carbide dispersed in different areas throughout. But although we are not able to give a very convincing explanation as to why it is, the presence of that hard brittle carbide in such small quantity raises the mechanical strength of the iron from 14 tons to nearly 30 tons. It has also been found over the last two or three generations that if you still further increase the carbon content of the steel you will further increase the strength until you reach a percentage of 0.9% of carbon, when you have what is called a "pearlitic " matrix. In such a steel you have a critical composition of what we know as a " eutectoid " composition. But you see, as you continually harden up the steel—making it stronger by adding the carbon content— you lose ductility ; and after all, you cannot get beyond a certain hardness. The intrinsic hardness induced by the precipitation of carbide even to saturation would only take you up to 60 to 65 tons per sq. in., and if you go as far as that, it is at a very great sacrifice in ductility.

By hardening and tempering the steel you obtain properties very greatly in advance of the properties obtained by simply increasing

Leeds, 24 October, 1938; London, 20 March, 1939

TABLE I.—EFFECT OF ALLOY ADDITIONS UPON THE TENSILE

Type of Steel	Typical Composition, %						
	C.	Si.	Mn.	Ni.	Cr.	Mo.	V.
0.28% Carbon Steel	0.28	0.20	0.75	(0.22)	—	—	—
0.55% Carbon Steel	0.55	0.23	0.58	(0.16)	—	—	—
1½% Manganese Steel	0.29	0.19	1.4	(0.21)	—	—	—
1½% Manganese - Nickel - Molybdenum Steel	0.30	0.33	1.18	(0.55)	—	0.28	—
1% Chromium-Molybdenum Steel	0.32	0.13	0.55	—	1.05	0.25	—
3% Nickel Steel	0.30	0.21	0.50	2.87	—	—	—
3½% Nickel low-Chromium Steel	0.43	0.19	0.64	3.58	0.20	—	—
3% Nickel-Chromium Steel ...	0.31	0.14	0.70	3.40	0.70	—	—
3% Nickel - Chromium - Molybdenum-Vanadium Steel ...	0.23	0.18	0.55	3.04	1.47	0.53	0.19
3% Nickel - Chromium - Molybdenum Steel	0.32	0.27	0.63	3.44	0.83	0.31	—
4½% Nickel - Chromium - Molybdenum Steel	0.28	0.15	0.50	4.20	1.50	—	—

the carbon content. Harden the steel, and then progressively temper it to the temper you require, and you have a very interesting and useful condition of metal. But you can only harden and temper a carbon steel of very thin section. If the steel becomes heavy in section it is hopeless to expect that a carbon steel could achieve the results of hardening and tempering, even on the surface.

If you add several elements to steel, elements such as nickel and chromium, you entirely alter the physical and mechanical changes which take place in that steel during cooling . You modify the facility with which the solid solution of " austenite " present at high temperatures breakes down into a soft condition. You render the carbon change sluggish, and therefore by the addition of these alloys you are able to harden even the heaviest masses. For instance, the heaviest armour plates for our battleships and huge shafts used in turbine engineering are made in this way, and so on. The value of the addition of alloys to steel is that the alloys facilitate efficient hardening and tempering, and so make it possible to obtain very high tensile properties with very substantial ductility—a ductility for the same high tensile strength entirely out of proportion to the ductility which you can attain in the carbon steel.

I have been asked by Mr. Rowe, " When should you use alloy steels and when carbon steels ? "

Alloy steels are more expensive than carbon steels, and it is a very commonplace statement for me to make to you gentlemen

AND FATIGUE STRENGTH OF DIRECT HARDENING STEELS.

Typical Tensile Properties	On 1⅛ in. Dia. Bar							
Treatment of Condition	M.S. sq. in. (tons)	M.P. sq. in. (tons)	Elong. %	R. of A. %	Brinell Hard-ness Number	Izod Impact, Ft.-Lbs.	Fatigue ± tons/ sq. in.	Elastic Modu-lus, tons/ sq. in.
Normalised 870°C. ...	**35.8**	19.5	31.5	57	151	32	**14.9**	13,300
Normalised 830°C. ...	**46.5**	27.8	21	38	202	10	**19.0**	13,250
O.H.850°C., T.640°C. ...	**40.5**	29.1	31	59	187	85	**17.5**	13,300
OH.870°C., T.650°C. ...	**52.25**	43.0	25	66	241	91	**20.5**	13,300
O.H.820°C., T 680°C. ...	**53.8**	45.5	24.5	67	255	65	**22.0**	13,150
O.H.830°C., T.600°C. ...	**46.5**	37.4	25.5	58	212	74	**19.5**	13,150
O.H.850°C., T.570°C. ...	**63.8**	56.4	22	61	293	55	**27.0**	13,050
O.H.820°C., T 600°C. ...	**60.1**	54.5	22	61	277	68	**26.5**	13,100
O.H.850°C., T.640°C. ...	**73.9**	68.7	21.5	69	340	48	**32.0**	13,200
O.H.850°C., T.660°C. ...	**75.2**	69.6	20	54	349	46	**32.5**	13,200
A.H.820°C., T.250°C. ...	**106.0**	85.0	12.5	45	495	15	**45.0**	13,150

as an axiom that you should not use alloy steels unless you are compelled to do so. The steel makers of Sheffield, selling special steels at special prices, cannot expect you to use special materials when ordinary materials would function. If you can use an ordinary mild steel or a carbon steel do not use an alloy steel, because when you go into alloy steels you are going into a technology which requires understanding. For instance, you will find some plants engaged in making common steels and not alloy steels ; they make alloy steels without consideration of the real technology and difficulties, and therefore it is far wiser that you gentlemen should not use alloy steels unless the advantages to be gained by their use far outweigh the disadvantages to which I have referred. When should you use alloy steels, then ? One can answer that by saying if, for instance, you are making an aero engine you cannot build it without the use of alloy steels because you could not get the weight per horsepower which is necessary. To be able to make a connecting rod with a maximum stress of 80 to 90 tons per sq. in. or even higher coupled with substantial ductility means that you can dispose of quite a lot of weight. In fact, the weight of the aero engine to-day can be so low as 0.7 to 0.8 of a lb. per h.p. That is an amazing achievement, and it is typical of the direction in which you should look when you are thinking of alloy steels.

Table I contains a series of steels—a low carbon steel, a high carbon steel, manganese-nickel-molybdenum, nickel and nickel-

chromium steels. If you increase the maximum stress or strength by raising the carbon from 0.28% to 0.55% resulting in the maximum stress being increased from 35 to 46 tons/sq. in., you also reduce the ductility from 31% to 21%, and substantially lower the Izod value of impact strength. Now by way of contrast consider a typical nickel chromium-molybdenum-vanadium steel which has only 0.23% carbon to which has been added 3% nickel, 1½% chromium and some ½% molybdenum and ¼% vanadium. You can actually obtain from such steel a maximum stress of nearly 75 tons/sq. in. with a yield point of nearly 70 tons/sq. in. still with an elongation 21%. In other words, this high tensile steel possesses as much ductility as a carbon steel of only 46 tons per sq. in. tensile strength. But what is more, you can obtain an Izod value of something like 50 ft. lb. as against 10 ft. lb.

You will see that you as production engineers having in mind, for instance, the production of a part or a mechanism in which you want lightness and strength, can obtain a strength without anything like the weight by utilizing a complex nickel-chromium steel of this type. There are in fact many cases where manufacturers would be quite prepared to pay for the special steel on account of its improved ratio of strength to weight.

By further increasing the nickel and the chromium a little, you can actually obtain with certainty tensile strength in excess of 100 tons per sq. in., and still with an Izod value in excess of that which you obtain from a 0.55% carbon steel having a maximum stress of 46 tons per sq. in. In this table you have, I think, typical examples of what alloy steel can do.

You may well say, " Yes, you explain that you keep the carbon content down by adding 3% of nickel and 1% of chromium ; you explain that the addition of these elements makes the carbon change quite sluggish, but why add molybdenum and why the vanadium ? " Experiment has shown that if you do not add molybdenum, for instance, and cool the steel very slowly after tempering, the Izod value will fall. So that the addition of molybdenum assists preventing " temper-brittleness." Vanadium, on the other hand, is found to give a steel a smaller crystal size and this is deemed an advantage from many angles. It has been said, and with truth, that a steel of small crystal structure behaves better under fatigue.

I have now outlined the general conception of a typical allow steel. Before we finish with the alloy steel, however, I would say this—that it is only fair to the technologists responsible for the production of alloy steel that when an important purpose is intended for such material, they should be consulted so that any special problems which may exist are properly taken care of.

There is another aspect of alloy steel which should also be mentioned ; the use of alloys in case-hardening steel. You might think,

" Well, if I take a piece of plain carbon steel, carburise it, and quench it, I get the hard case, and the soft interior, and I have got all I want." So you have, unless the part is being submitted to very high stress. It is quite conceivable that the conditions of service may involve having to sustain stress which the hard case will bear, but which the soft underlying material is not strong enough to support, and then you get deformation and probably ultimate cracking of the case. Reference to Table II shows that if you add nickel to the case-hardened steel, nickel and molybdenum or nickel, and chromium, you can produce during the quenching operation a core of gradually increasing strength. The carbon case-hardened steel core will have a tensile strength just above 30 tons/sq. in. By adding 3% of nickel you can ensure that the new case-hardened steel will have a strength of 50 tons in the core and by using a suitable nickel chromium case-hardening steel you can ensure that you have underlying the case a hard matrix with a tensile strength around 90 tons/sq. in. So I think you will concede that the alloys have entered into the production of case-hardened steel with great success, in that they have permitted the core under the case to be given greater stiffness so that the case hardened part itself can stand up to much heavier work.

The hardening of steel by " nitriding " is another instance of when to use alloys. Let us compare a carbon case-hardening steel with a special alloy steel which, instead of being given surface hardness by carburising, is surface hardened by heating in ammonia gas at 500° C. The addition of the alloys aluminium, chromium and molybdenum, nickel and vanadium in suitable proportions enables the engineer to fabricate a part and then, instead of heating it to 900 to 920° C. for carburising simply to maintain it at 500°C. in ammonia and obtain very intense hardness. The time taken is certainly longer, but the hardness achieved in the case of chromium-aluminium steel is generally over 1,050, as compared with 600 to 780 in the hardened carburised case ; also owing to the low temperature at which the hardening is carried out warping is practically absent, whereas of course you know that in quenching case-hardened articles great care is needed to prevent cracking. A further interesting characteristic of the hardened layer produced by nitriding chromium steel is that the hardness is unimpaired with the rise of temperature until you attain temperature in excess of 550° C. On the other hand the case-hardened surface begins to temper at temperatures above 200°C. I do not think I need say more to justify the alloy steels as such, and I trust that I have given an answer to Mr. Rowe's first question.

Dr. Hatfield then showed a number of slides showing different types of trouble encountered in case-hardened parts.

Fig. 1 shows a fracture of a part made in 5% nickel case-hardened

TABLE II.—EFFECT OF ALLOY ADDITIONS UPON THE CORE STRENGTH OF CASE-CARBURISED STEELS

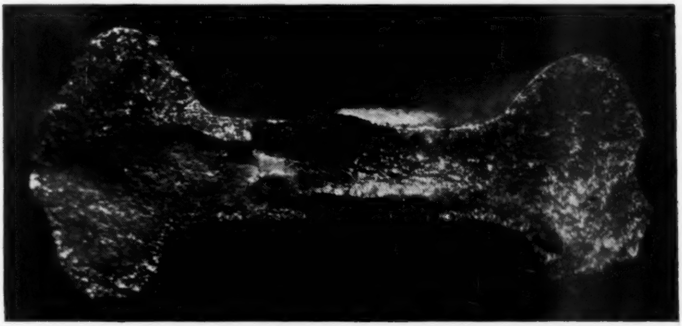
Type of Steel	Typical Composition, %						Typical Tensile Properties On 1⅛ in. Dia. Bar					Brinell Hard-ness Number	Izod Impact, Ft.-Lbs.	Fatigue ± tons/ sq. in.	Elastic Modu-lus, tons/ sq. in.
	C.	Si.	Mn.	Ni.	Cr.	Mo.	Treatment or Condition	M.S. tons/ sq. in.	Y.P. tons/ sq. in.	Elong. %	R. of A. %				
Carbon C.H. Steel ...	0.12	0.18	0.65	(0.10)	—	—	W.Q. 900°C., „ 760°C	**31.3**	17.2	33	61	137	85	**14.0**	13,400
3% Nickel C.H. Steel ...	0.12	0.15	0.50	3.10	—	—	O.Q. 840°C., WQ. 760°C.	**49.3**	35.1	20	49	217	70	**20.5**	13.050
5% Nickel C.H. Steel ...	0.12	0.14	0.30	4.9	—	—	O.Q. 830°C., W.Q. 760°C.	**58.8**	40.1	18	48	269	28	**26.0**	13.000
5 Nickel-Molybdenum ... C.H. Steel	0.15	0.16	0.37	5.0	—	0.40	O.Q. 830°C., „ 760°C.	**82.4**	75.2	17	59	375	59	**36.0**	13,000
1¼% Nickel-Chromium C.H. Steel	0.14	0.21	0.40	4.49	1.20	—	O.Q. 830°C., „ 760°C.	**89.0**	73.0	18	64	418	30	**39.0**	13,100

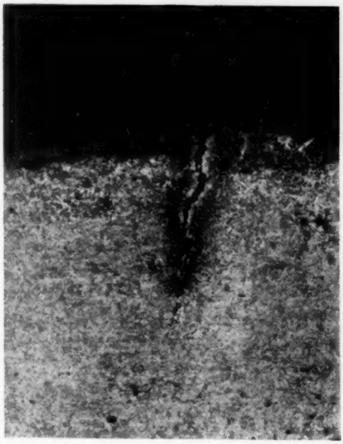
TABLE IV.—EFFECT OF GRAIN SIZE UPON TRANSVERSE PROPERTIES OF "45" CARBON STEEL 6 in. sq. BILLET

Treatment	Coarse Grain					Fine Grain				
	Y.P.	M.S.	E1.%	R/A.%	Izod	Y.P.	M.S.	E1.%	R/A.%	Izod
As rolled, T.650°C.	29.8	**51.4**	**10.5**	14.5	2, 2, 2	30.2	**53.8**	**6**	8	6, 5, 3½
Normlsd. 900°C., T.600°C. ...	38.4	**59.4**	**8.5**	13	6, 6, 6½	36.6	**56.4**	**7**	10	5, 5, 4
O.H.850°, T.600°C.	57.8	**64.4**	**10**	20	7, 7, 7	51.9	**61.5**	**11**	21	11½, 12, 11
N.900°, O.H.850°, T.650°C. ...	46.4	**53.2**	**4.5**	9.5	14, 16	44.2	**48.2**	**2.5**	6.5	7, 10, 21

Fine grain steel treated with 1 lb. of aluminium/ton of liquid steel: otherwise exactly similar.

steel. Now that fatigue fracture was due entirely to over-stressing and I have put that slide in to remind me to tell you that I have been examining failures for many years and in over 90% of the cases, failure has been due to over-stressing. Fig. 2 illustrates a case of



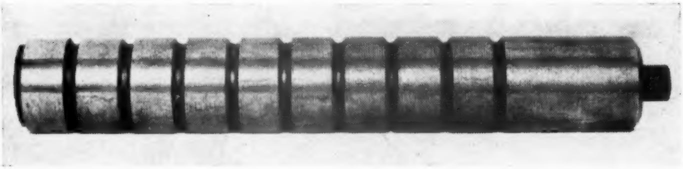


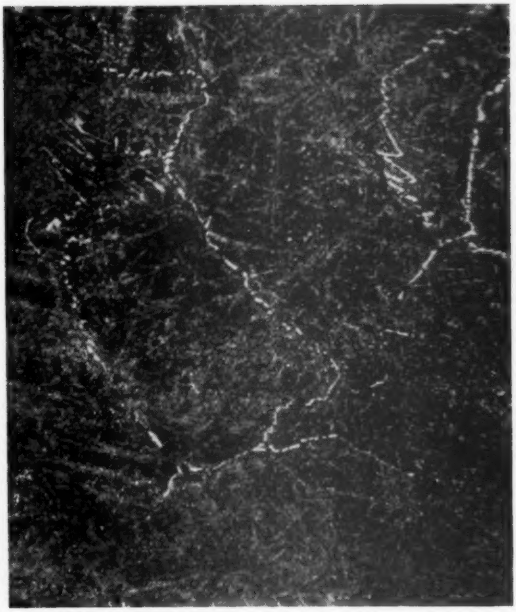
x 100

Fig. 1—Crack in 5% Nickel C. H. Steel Valve Rocker Surface diamond hardness 690/707 and microstructure satisfactory. Crack due to overstressing in service.

failure from surface cracking induced through the fact that in the carburising process the operation was allowed to continue for too long and a network of free carbide resulted. Free carbide in that form is very dangerous and leads to local cracking. Fig. 3 shows a

very interesting case where the presence of non-metallic inclusions in local patches leads to a differential hardness in the case-hardened surface.



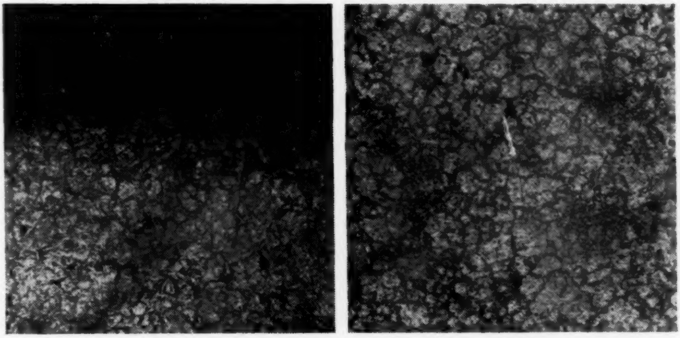


x 200

Fig. 2—Surface cracks on a 4½% Nickel-Chromium C.H. Steel Spindle caused by excessive carburisation. A lower carburising temperature would result in a less brittle case.

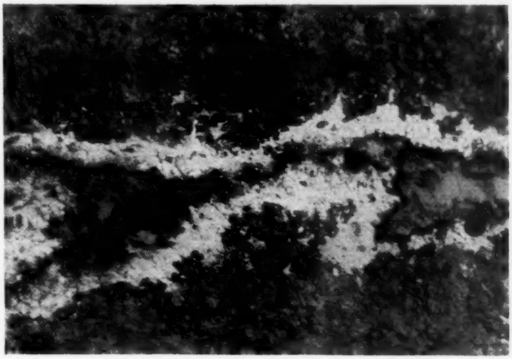
Fig. 4 represents a photomicrograph of a ghost—a very material one. The decarburised zone around such an inclusion, if on the surface, will become a soft spot. We pour liquid steel into the mould. It freezes solid and so we get the initial form of steel which we begin

to roll and forge down to the dimensions ultimately required. But the liquid steel we pour into the mould is never quite a pure liquid. Oxygen plays a very important part in the making of steel and disseminates in fine dispersion throughout the liquid. Deoxidisers are



x 200 x 200

Fig. 3—Illustration of lack of uniformity of carburised case of mild carbon C.H. Steel, due to presence of and excessive quantity of non-metallic inclusions.



x 200

Fig. 4—Typical micrograph of a "Ghost" The decarburised zone around the segregate will be noticed, if on the surface this will become a "soft spot."

added and these "fix" the oxygen in the form of various oxides of silica, manganese, and iron. Further in addition to the oxides we also have a certain amount of sulphur, up to 0.03% or 0.05%, which

is present in the form of manganese sulphide which remains as a separate entity or inclusion in the steel. When the steel freezes, therefore, there are present both oxides which combine and form minute particles of slag, and sulphides existent as non-metallic inclusions. If you take one of these ingots and section it along its axis and examine it, you will find that those non-metallic inclusions form streamers extending through the length of the ingot.

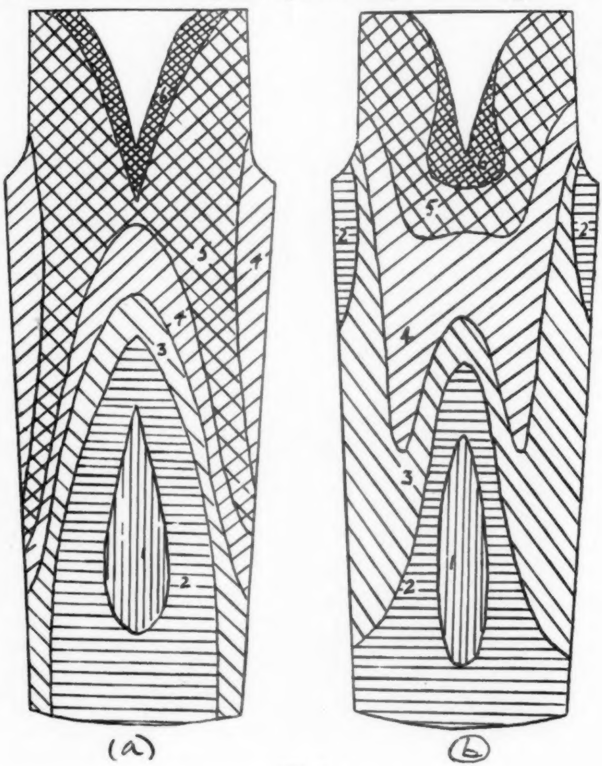


Fig. 5.

It is important that I should talk about these non-metallic inclusions because engineers have studied this subject very carefully. Many have assumed that steel is a homogeneous elastic solid, but this assumption is not valid. Steel is not homogeneous : it suffers from the disabilities inevitably resulting from differential freezing. You

know that if you freeze a salt solution the crystals settle out and the first ones are a good deal purer than those which freeze last. If there is any dirt in the salt water you will find it adjoining the crystals. The same thing occurs in steel and the non-metallic matter, carbides, and other impurities in the steel segregate out.

Now without troubling you with all the details of the investigations I will show you the result of studying the degree of heterogeneity of a number of ingots as regards all the elements which are present. Generally speaking those elements which segregate tend to do so in a manner indicated by the two diagrams in Fig. 5. You have the pure zone in the lower half of the ingot, surrounded by a less pure zone, with a relatively impure zone extending in cylindrical form down the interior of the walls of the mass. Then you have a richly segregated area at the top. When you deal with small masses, of course, the differential freezing effect does not come into play to anything like the same degree, but nevertheless, it is not entirely absent.

The sections were etched and all the individual crystals were reproduced. You see that the area of fine crystallisation exists only towards the bottom of the first ingot ; but extends nearly to the top of the second ingot, and that there are also several other major differences in the manner of crystallisation of the two ingots. Both were cast from the same steel, the only difference being 40° in temperature such as casting temperatures, rate of teeming, shape of mould—so you will see that such factors enter into the production of commercially perfect steel ingot.

(*The lecturer then showed a section through a special nickel-chromium-molybdenum-vanadium steel ingot produced for aero crank-shafts, in which the heterogeneity had been brought down to very low limits indeed*).

Briefly, without going into the matter in such considerable detail, I will try and deal with the two other questions which were put to me. The first of these questions related to the non-metallic inclusions. Now from my remarks so far you will, I am sure have become satisfied that as oxygen and sulphur are inevitably present in the steel, the finished product must contain non-metallic sulphides and oxide inclusions, and amount and number of them will be determined by the success of the de-oxidation and de-sulphurisation of the steel. Now if you get the sulphur content very low, and the steel as completely de-oxidised as possible, you have a fair chance of having a very low inclusion count. It has been suggested that a test might be devised which would include the method of quantitatively evaluating these inclusions, and such methods have been worked out from time to time.

I think that whilst an inclusion count is of value, and indeed, in all the quality steel-works attempts are made to keep the non-

TABLE III.—COMPARISON BETWEEN STEELS OF SIMILAR

Steel	Aluminium Additions			Grain-Size Index	Heat-treatment	L. of P. tons/ sq. in.
Siemens furnace 0.25%	—	—	—	3	As received	**15.9**
	—	—	0.025%	7-8	,,	**12.6**
Carbon Steel	—	—	—	3	N. 930°C.	**15.1**
	—	—	0.025%	7-8	,,	**18.3**
	—	—	—	3	W.Q. 900°C. T. 500°C.	**24.6**
	—	—	0.025%	7-8	,,	**27.0**
	—	—	—	3	W.Q. 900°C. T. 650°C.	**23.5**
	—	—	0.025%	7-8	,,	**20.6**
Electric furnace	0.014%	0.007%	—	3	O.Q. 830°C. T.550°C., W.Q.	**47.8**
	,,	,,	0.025%	7-8	,,	**50.0**
3½% Nickel	,,	,,	—	3	O.Q. 830°C., T.630°C., W.Q.	**33.6**
Chromium	,,	,,	0.025%	7-8	,,	**19.0**
Steel	,,	,,	—	3	O.Q. 830°C., T.630°C., F.C.	**45.2**
	,,	,,	0.025%	7-8	O.Q. 830°C., T.630°C., F.C.	**32.1**

metallic matter at as low an amount as possible by means of a micro-study of this character, yet experience has shown that it is quite impossible to reduce the matter to such physical conditions of examination that you can always get the same result twice or that two men can obtain the same result on the same specimen. Now when this matter was under consideration many months ago I formed a committee based on the Ingot Committee of the Iron and Steel Institute, and the committee included representatives of our principal steelmakers, our principal aero-engine builders, and of Government Departments.

We took probably a dozen samples of steel representing the steels used in aero engine building. Now the actual samples were taken in juxtaposition and were sent to twelve laboratories—to twelve men whose technical distinction was not to be challenged—and they were all invited to study the inclusions present on the lines which have just been discussed, and to record the figures which they obtained. There was, however, so great a disagreement in the results that, at any rate for the time being, it is deemed impracticable to have a quantitative means which successfully fills the object in view.

Take the " 40 " carbon steel for instance ; results obtained by different laboratories were 64, 56, 65, 76, 85, 92, 87, 54, 87, 72, 52, 58, 29, 34, 37, 55, 52, 59, 74, and 66. The disagreement is far too

COMPOSITION WITH COARSE AND FINE GRAIN.

Y.P. tons/ sq. in	M.S. tons/ sq. in.	Elong. %	R. of A. %	Izod	Brinell	Remarks
19.6 19.0	33.0 32.4	30 30	45 47	**74, 76, 66** **77, 84, 79**	148 146	No difference in impact strength. Coarse grain gives *higher* elastic limit.
19.4 20.8	32.0 32.4	31 31	48 49	**62, 49, 66** **78, 83, 79**	143 146	Fine grain size shows slightly higher impact and elastic limit.
30.0 28.0	**43.1** **40.1**	25 32	60 66	**80, 80, 70** **103, 110, 103**	196 179	Higher impact strength of fine grain steel accompanied by lower tensile strength.
24.0 22.5	**35.2** **32.8**	31 39	71 72	**95, 100, 100** **89, 100, 100**	159 146	No increase in impact strength of fine grain steel despite lowered tensile strength and elastic limit.
59.8 63.0	**68.8** **68.1**	17.5 16.5	55 53.5	**43, 43, 45** **53, 54, 56**	321 321	Slightly higher impact strength and elastic limit in fine grain steel.
47.0 42.7	**58.0** **59.2**	22 20	58 50	**85, 90, 83** **86, 85, 88**	248 239	Greatly reduced elastic limit in fine grain steel.
52.6 48.7	**61.0** **57.2**	21 23.5	59 59	**60, 58. 57** 70, 65, 71	269 269	Slightly higher impact strength in fine grain steel, but considerably lower tensile strength and elastic limit.

wide. Take 65 ton nickel-chromium-molbdenum-vanadium steel. The figures ranged from 16 to 48. Such variability is not consistent with the consistency of results obtained from the tensile and other tests which form the basis for reception of materials.

So much for inclusion counts. Wherever anyone is interested, my organisation on behalf of our group is very glad to provide information as regards the non-metallic matter present in steel, always provided that those who require the information will be careful to lay down the conditions under which the observations are to be made.

Now as to the question of grain size. It has been discovered that by adding aluminium, vanadium and other deoxidisers to steel you can ensure a much smaller grain size than without the addition. For instance, we have performed an experiment in which 0.025% of aluminium was added to electric steel from the same cast as ingots which were cast without any aluminium at all. The grain size was 3 to 4 without the aluminium and 7 to 8 with aluminium. A similar experiment performed with Siemens' steel produced a grain of 3 without the aluminium and 7 to 8 with aluminium.

There has been one very great difficulty in interpreting the vast amount of data which has been brought forward of late on the effect of grain size on the property of steel. It has related to steel bars—bars of small dimensions—and a lot of the data (most of it in fact)

relates to longitudinal testing. If you test longitudinally, whilst you may get some increase in the impact value you also get a decrease in the maximum stress and the fatigue range although as revealed in Table III, the results are indeterminate. An interesting experiment, however, was performed on two 0.45% carbon steel bars 6 in. sq. which enabled the tests to be done transversely as well as longitudinally. The results of this experiment are reproduced in Table IV and reveal that by adding aluminium you produce small grain size but you also produce a great number of inclusions which during the rolling align themselves in the direction of the bar and substantially decrease the tranverse ductility of the material. I have already said that the addition of vanadium induces a small crystal size, and I regard a fine grain produced in such a steel by proper steelmaking technique to be in an entirely different category from fine grain structures obtained from adding aluminium in the last stages.

In this lecture, I have been showing you tables and charts, and they may give the impression that steel-making is an abstract science. I want now to show you a coloured film which illustrates the production of an ingot weighing 180 tons. I want to show you the actual conditions of heat and labour under which your production engineers expect us to carry on our art under the most scientific conditions : In other words, I want to bring you from the abstract to realities before you start the discussion, and to give you an idea of the magnitude of the engineering and manipulative problems involved in steelmaking as well as of the delicacy of the physico-chemical equilibria which govern the composition and quality of the product.

(*The colour film was then shown*).

Discussion, Yorkshire Section

MR. R. J. MITCHELL: We have problems connected with cold drawing dies on the one hand and with the complement of those tools on the the other—drawing mandrils. I am speaking of the non-ferrous tube industry. Naturally, we know something about how to make the tools, otherwise we should not have made so many tubes but some of us feel that the time has arrived when if only we could put our questions to the steelmaker intelligently enough we might make very signal advances in our technique.

My first question is, do I correctly deduce that where you have tools, which after all may be regarded as stressed structures subjected to a combination of intense pressure with heavy tension stresses, there remains no shadow of a doubt that some type of alloy steel is the best material to select for such a purpose? I ask that question because in our shops quite lately we have been called upon to make tubes out of non-ferrous alloys approaching in mechanical strength the old conception of steel, and we have come across some very considerable workshop troubles due to the fact that tools which in the old days worked perfectly well began strangely to fail, and in rather spectacular ways in some cases. Dies which had given perfectly good results for twenty years now mysteriously began to fly across the shop in several pieces, with very dangerous possibilities. Plugs and mandrils and rolling dies behaved likewise.

For cold drawing dies, very broadly speaking, what class of steel would Dr. Hatfield recomend? I am not speaking of an exact type of steel, but broadly speaking, what *class* should be used? For cold drawing mandrils which are subjected to very intense abrasion and at the same time to such heavy surface forces that actual indentation of the mandril can take place, I would ask the same question, and then I would like to ask a complementary question; where you are employing probably the largest concentration of mechanical forces which are met with, I should imagine, in any manufacturing process—that of the heat extrusion of very tough alloys under pressures of many many tons to the sq. in.—is there any particular class of steel which one ought primarily to think about, and conversely are there certain classes of steel which for fundamental reasons it is quite useless to think about?

DR. HATFIELD: I congratulate the speaker on his questions. What he is really asking me to do is to give him here and now concrete answers to specific problems on which he has spent his lifetime in working. He is bringing me from the general to the particular. I can only answer him in general terms at the moment, but I

would be glad to give him an opportunity of cross-examining me for a whole day. But first I would like him to explain why a soft non-ferrous alloy will indent a hard steel mandril and what lubricants, if any, are used on the job. I must ask these things to show the complexity of the questions, which can be answered only with full knowledge of the facts. I have dealt in my talk to-night with mechanical strength, not with resistance to abrasion or wear, and the two characteristics are extremely different, as you know.

In general terms, the high carbon and carbon-chromium steels are very good for resisting wear, as shown in the railway tyre, and such steels are used for mandrils, but then I would like to study in closer detail exactly what the conditions are before giving a final answer to such a specific question.

Dr. Pickup: I notice Dr. Hatfield has been talking about the manufacture of steel in large ignots, whereas I am interested in steel in the finished components. With regard to case hardening. Dr. Hatfield mentioned the question of nitriding, and I should like to have his views with regard to the relative merits of, say, a gudgeon pin case hardened and a gudeon pin nitrided. What is the advantage or disadvantage of having a gudgeon pin carburised in the bore? I believe certain manufacturers are to-day using gudgeon pins which are carburised in the bore. Another question I would like to put about gudgeon pins is that of mechanical stress or maximum stress. Some years ago I was doing some work on the burning of steel and I found that when the steel had been burnt it was not possible to regain the physical properties of that steel by any heat treatment. The only way the physical properties were obtained was by first forging down the steel again followed by heat treatment. Now the interesting part was this—that the maximum stress was the same after heat treatment but the impact test was very low, and it was only after forging the steel that we got the physical properties back again. I have come to the conclusion that the maximum stress is only of value for determining or defining the fatigue stress of the steel; and for the controlling heat-treatment, a Brindell or Vickers-Diamond test will give a very good control of the heat-treatment of steel, along with an Izod Impact Test.

Dr. Hatfield: With regard to gudgeon pins, there are, of course, gudgeon pins for heavy diesel engines and gudgeon pins for motor-cycle engines. You will appreciate that one cannot generalise—one has to know specifically the nature of the gudgeon pin and the duty which it has to perform. Taking it as a general question, it is quite clear that the nitrided skin occupies only a comparatively small depth. Case hardening goes to a greater depth and, therefore, this mechanical strength which you are requiring can in some measure be obtained on an ordinary carbon steel by virtue of the hard carburised surface. Strength to support the load is obtained

in a " nitralloy " steel by the presence of alloys which give a hard tough core. So it is really a question of choice as regards what particular circumstances you are called upon to meet.

Dr. Pickup : I forgot to mention that actual hardness of the steel is measured by, say, a Vickers-Diamond test, but that is not a criterion of the wearing qualities of the gudgeon pin.

Dr. Hatfield : The choice of case-carburising or nitriding steel depends upon the particular case. If it is a case of close tolerances with no possibilities of shock, then the nitrided surface will behave very well indeed, provided it is adequately supported upon a strong core inside. You can have nitrided steel which gives various degrees of strength in the core but unless you have a proper steel to reinforce the thin nitrided layer, the part may fail.

With regard to the burnt steel, we call steel " burnt " if it is in part liquified throughout the mass. In that case you cannot really hope to obtain the original properties unless by forging you give the steel the same thermal and mechanical treatment which you gave to the ingot, because that metal which has been fused freezes again and is in fact analagous in condition to the frozen ingot. It may not perhaps have occurred to you but when you forge an ingot, besides submitting it to deformation you also put it through a thermal treatment. It is an interesting experiment to heat steel to forgings heat, but not to forge it. Let it cool down and see what the mechanical properties are, and compare them with those of the unforged, untreated ingot. When you re-forge the burnt steel you are actually submitting it to a very severe heat-treatment as well as mechanical deformation. It is not astonishing, therefore, that the forging operation modifies the impact test.

In your observation about the maximum stress being of little value except insofar as it determines the fatigue strength, you are in effect saying that the fatigue strength has a definite relation to the maximum stress. The maximum stress is far more easily determined than the fatigue limit, and therefore you must concede that the maximum stress is quite a useful figure to have. This is particularly so because when you determine the maximum stress and at the same time determine the yield point, which is the commercial rather crude sort of way of determining the elastic range. The tensile test also gives you the elongation and the reduction of area, these being very important as an indication of the properties of the material. The tensile test, therefore, gives you a measure of the strength, the elastic range, the fatigue limit, and the ductility of the steel, and in my opinion it entirely outweighs all other information. I regard the Izod test as supplementing this information in a certain direction from a rather academic viewpoint, and the Brinell test is useful if you have not the facilities for doing a tensile test.

Mr. Forrest: As Dr. Hatfield knows, it is common practice to test finally the surface for hardness. Is it possible to obtain pot hardness on the surface where the hardness will be, say 60 to 63 Rockwell and have the hardness of the ordinary carbon case hardening steel in an alloy steel, both having the same Rockwell hardness but in the case of the alloy steel the surface may be "tacky," so that the file will not slip over it to the same extent that it will over the carbon case hardening steel? One other point is with regard to fractures of case hardened parts. We know that many engineers are still influenced by the fibrous fracture and I would like to hear what Dr. Hatfield has to say about that.

Dr. Hatfield: I would answer your first question by saying that I believe it to be a fact that, leaving out of the subject all question of nitriding and confining oneself to the ordinary steels, a properly carburised and quenched plain carbon case steel gives the greatest hardness that can be obtained. I think it is true to say that a 5% nickel steel, carburised and hardened would probably deserve the description of being slightly "tacky" compared with the carbon steel under the conditions which you mention. On the other hand do not forget that the slightly less hardness—it is very slight—of the nickel steel is accompanied by a much greater strength in the core which I believe, in fact practice shows, compensates, for the slight reduction in hardness in a great many applications.

Mr. Forrest: I quite agree with your point, only quite a number of inspecting engineers demand file hardness as distinct from, say, the Rockwell figure. You must have file hardness on the surface.

Dr. Hatfield: It is a good plan to ask them to define what "file hardness" means, because file hardness is a very empirical term. It depends for one thing upon the file and how it is used. As a production engineer I am surprised at your accepting such a test. You mention the fibrous core of the case-hardened part. Surely we have got past the time when fibre should be seriously considered in case-hardened parts? One has to go back to the Dark Ages of metallurgy when all new materials were critically compared with wrought iron; and a tough but very dirty steel of a soft character on breaking gave the appearance of being, in fact, wrought iron. You must get away from any idea of fibre which is simply steel full of non-metallic inclusions. The fibre which is admired by some simply belongs to tradition.

Mr. Hammond: I have one point which I would like Dr. Hatfield to express his opinion upon—it also bears upon the question of the retreatment of case hardened material and it is with regard to the treatment in a case hardening bath of the nature of a cyanide as distinct from the normal high carbon material in the pack hardening process. It has been stated by some authorities that some injurious effect results from the immersion of certain alloy and carbon steels

in the cyanide bath such as the impregnation or combination of nitrogen compounds or something of that nature which seriously affect the Isod value of the resulting part. I would be pleased to have Dr. Hatfield's opinion on that question.

Dr. Hatfield: I know that the cyanide process is used reasonably extensively but taking case-hardening as a whole it is a minor procedure. Nevertheless, I regard it, from all I know of it, as a satisfactory procedure and I am surprised that it is suggested that the very short immersion which is given in the cyanide should permit of the interior material being damaged in the way you mention. I have no evidence to support the statement which you have heard.

Mr. H. C. Newell : I was interested to learn that Dr. Hatfield is such a staunch advocate of the tensile test. The hardness tests have their uses but they are, to my mind, limited. It seems to me that, fundamentally, there is little relationship existing between a test which abrades the surface as in the Brinnell ball test and a test which shears the surface as in the diamond. Since there are many different ways of determining hardness it seems to me that the first thing we should do is to define " hardness." Possibly Dr. Hatfield could help me in stating a satisfactory definition. The same difficulty arises in the case of the Izod and Charpy impact tests and Professor Southwell's experiments on the Oxford machine constitute an attempt to correlate these. I was privileged to see the Oxford machine demonstrated some years ago and was impressed by the ingenuity of design and the uniformly good results obtained by this equipment. There is, however, the difficulty of correlating the results obtained in the laboratory under ideal conditions and those obtained in practice where usually the material is subject to compound stresses. The only other question I would like to ask is with regard to " grain size." What is a unit of " grain size ? "

Dr. Hatfield : In reply to Mr. Newell regarding my definition of hardness I would say that it is a very big subject, as all of you know, and there are various kinds of hardness. Even wear-resistance can be regarded as one form of hardness, but in all my work for many years I have regarded hardness in terms of " resistance to penetration," which can be quantitatively measured by the Brinell test. After all, these tests are of an arbitrary character and when you are trying to correlate one form with another all you can do is to take standard samples of known hardness according to one type of measurement and carefully determine by experiment what the hardness is when determined by another method.

Mr. Newell : Is not that rather assuming that you have got the perfect sphere ?

Dr. Hatfield : I have regarded for practical purposes of research the Brinell penetration test as the one well-tried, well-understood method of determination. I admit that the Rockwell has come in,

but after all, the Rockwell does not give any information which the Brinell does not. If you want to go deeper into the subject the thing to do is to get someone to come and give you a lecture on what hardness is. It has been done by many able people and they have talked all evening, and the discussion has gone on until closing time, and finality has not been reached. The whole position is in a state of flux, but I understand what is meant when we speak of " resistance to penetration " of a hardened steel ball or a diamond pyramid, and this is an index of hardness which is very satisfactory.

Mr. Newell spoke of the fact that those tests produced a set of conditions which did not apply in any engineering moving part and I entirely agree with him. It is very interesting, too, that you engineers designing moving parts—parts which have to be stressed—do not often consider the elongation or reduction in area of the steel. The only thing that appears to matter to you gentlemen is the fatigue range of the material. You simply impose the other tests to make sure that you have got something which has some of the properties of the old wrought iron which we left so long ago.

Dr. Pickup: With regard to this hardness question, I was reading an American paper this week-end dealing with some research work done there on " absolute " hardness. It was concerned with eliminating the cold work done, during the penetration, when making a Brinell test. After making the impression in the usual way, the sample was annealed to remove the cold work. Then the ball was placed in the same impression and the load applied again. On measuring the diameter it was found to be greater than originally. The sample was again annealed and this procedure repeated. Again the diameter was found to have increased. In this manner, 10 annealings were necessary before the diameter of the impression became constant. From the final reading, the authors obtained what they claimed to be the " absolute " hardness, as far as it can be obtained commercially. Obviously, this method could not be used on say hardened steel, because the hardness required would be impaired with the annealing treatment. I mention this work, as a matter of interest, since Brinell hardness has been raised in this discussion. It does bring out the fact that cold work is produced whilst making the usual Brinell test, this can effect the accuracy of the results.

Dr. Hatfield: It is very interesting, but I would submit that it is not on a commercial scale. Of course, when you press a hardened steel ball into a steel surface then take it away and measure the impression ; you have submitted that steel to very drastic deformation. You have work-hardened it locally and left residual stresses of considerable magnitude. Annealing will release those stresses and recrystallise the steel ; so the American is simply working out

by patient experiment over a long period of time something which I have taken for granted for years.

DR. PICKUP : These workers term it as " absolute hardness."

DR. HATFIELD : It is a misnomer. " Hardness " can be arbitrarily defined as " resistance to penetration," as " scratch hardness " as sclerescope " elastic hardness " and in several other ways, but no hardness test which I know can be regarded as recording a precise physical characteristic of the material.

MR. A. SYKES : It is a very pleasant duty to have to propose a vote of thanks after such a lecture as we have had this evening. We are extremely fortunate to be able to have a lecture from a man of such eminence as Dr. Hatfield.

I would like to add one or two questions. I am afraid we are inclined to ask questions of the schoolboy type, so that if we do ask anything which is very much schoolboyish we shall not feel offended if Dr. Hatfield treats us as schoolboys. Does Dr. Hatfield regard the Izod test as being of very real value ? What relation does it bear, if any, to fatigue strength—is it fatigue strength we are rather hazy about ? The results of fatigue we generally see in what we call a creeping fracture starting at the edge of a piece of material and going right through. What is it that starts the fracture in the first place ? Have we stressed the material too much, or is it due to some other local concentration of stress ? Has it in all cases gone beyond the elastic limit when fatigue takes place, and could Dr. Hatfield tell us whether for the purpose of avoiding fatigue the most important feature is a high elastic limit regardless of elongation or Izod value ? We are sometimes tempted to think " Is there such a thing as fatigue, or is it purely elastic failure ? "

There are one or two more simple questions. What is it that causes hardness when we quench a piece of steel ? Why does it become hard, and what is it that causes distortion on quenching ; is it uneven cooling with changes in section ? Dr. Hatfield gave us some interesting information on the question of grain size. I would like a little further enlightment on the measuring of grain size. What is its effect on hardness ; what is its effect on freedom from distortion ?

CAPTAIN L. J. SARJEANT seconded the vote of thanks.

DR. HATFIELD : I do very much appreciate the kind way in which Mr. Sykes and Captain Sarjeant have spoken of my effort this evening. I can assure you that it has been a great pleasure to me to come and hear what you have to say, and it is quite an exercise to me to make a suitable reply in each case. There is the matter of the Izod test —is it of any real value ? What is its relation to the fatigue strength ? What is the cause of an initial crack ? And would the elastic range of the material be expected to take care of such a case if it were sufficiently high ? Mr. Sykes has very neatly skated over the

primary question which any designing engineer would want answering, and I would say that the pursuit of a high impact value has led and is leading the engineering world into much trouble because you obtain a high Izod value only at the expense of having very high residual stress in the finished parts.

You all know that the way to get a really high Izod value is to quench out your finished part from the tempering temperature. If you cool quickly in your final treatment then you obviously cool the outer layers of the article whilst the inside is still hot and, therefore, the outside of the article takes a final dimension in excess of that which it would take if the inside were cold. The inside then cools down and contracts, but as the outside has already taken its dimensions you obviously have serious stress set up between the outside and the inside of the piece. If, in addition, you do not have symmetrical heating, you also have more or less unbalanced stress and consequent distortion. These stresses are already there in advance of those which you are going to apply to the finished part in service.

Now as to the exact value of the impact test. I do not know whether you are aware of it, but if you were going up to London to-night at 60 m.p.h., bumping over one rail joint after another, the tyres of the train will be of high carbon steel which has a very low impact value of something like five or six foot-lbs. Furthermore, those railway tyres under service conditions develop a very hard layer which may crack on the surface, and if you examine many railway tyres you will find that their surface consists of a mosaic of such small cracks. They are not of great depth, but they are there. Here you have an actual practical illustration of a low impact steel subject to stress when notched, and yet you can have your dinner or sleep on the train without any fear of the tyres breaking up. That is the answer to the impact question.

As regards the formation of a crack, it is the resistance to initial cracking which is important. If we take a 10 mm. square test piece and put a notch in it, you may have that material in a low impact value, and only five or ten foot-lbs. of effort are required to complete the crack through the specimen. But if the crack has not started then the amount of energy required to fracture it would be about 200 foot-lbs., and there you have a clear demonstration of the proper place in which you ought to put an Izod test. By increasing the elastic range you increase fatigue strength. Fatigue failure arises from high skin stress being in excess of that which the material can withstand, and by alternate stretching and compression the outer layers are destroyed. If you increase the elastic range of the outer layers and increase the hardness you will most likely overcome what has been fatigue failure.

The cause of hardness in quenching steel is a big subject, but the modern conception is that when you heat the steel to a critical point it becomes a solid solution, and when you quench it you really obtain a complex product which we do not properly understand, but one that is magnetic, and under the conditions of quenching from high temperatures the atoms composing the metal are in a condition of very severe internal stress. We tend to associate hardness with the strained condition of the crystal lattice, and I think this conception may ultimately be proved to be true.

The effect of inherent grain size on hardness and distortion come next. I do not think that grain size as such has much effect on distortion. The unit of grain size is obtained by taking a standard volume and determining the actual number of crystals in that volume. As for the effect of grain size on hardness, it is well known as a general law in metallurgy that the single crystal is the softest form of metal. A crystal aggregate is very much harder and stronger than a single crystal, and the hardness appears to be greater with the finer crystalline structure.

Discussion, London Section

Mr. L. W. Johnson : I should like to draw attention to the section of the ingot of alloy steel which Dr. Hatfield showed us, as it is remarkable for its consistency, cleanliness and lack of pipe. This takes me back a good many years ago when such ingots did not exist and it was necessary to section the ingots down in two planes, in other words to quarter them in order to obtain sound steel for important aero engine components. That was a very expensive method, and I think we owe a great deal to the work which Dr. Hatfield has done in enabling one to get over that problem.

Another point occured to me when he was showing a diagram giving the effect of temperature on the tensile strength, and that was that it was noticeable that when the temperature was increased the Izod value also increased. I would like to ask him whether, in machining steel, in view of the fact that the temperature is increased in spite of the use of cooling, the fact that the Izod value also increases makes the machinability of the steel rather more difficult.

Dr. Hatfield : Thank you Mr. Johnson. Mr. Johnson is a very old friend of mine, and I know that he himself did very good work when he was in the steel industry. With regard to the machining of steel, that is a very good idea that came to your mind whilst listening to the lecture ; that increased impact value with increasing temperature might under certain conditions of machining make it more difficult to machine such steel. I will cap it with another idea which is that in the free-cutting steel the slag inclusions introduced into the furnace tend effectively to lower the Izod value, but as a matter of fact I do not know whether there is anything in what either you have said or what I have just suggested.

Mr. J. Loxham : I should like to add my tribute to the work Dr. Hatfield has done and to compliment him on the excellent paper which he has given us to-night. I have three questions to ask. Firstly, has any theory been formulated which explains the phenomena usually referred to as temper brittleness in nickel chrome steels ? Most members will know that if a small chrome steel is hardened and tempered to below 200°C:, it has a high tensile strength but only a moderate Izod value. Tempering to 300°C. slightly reduces the tensile strength but reduces the Izod value to a dangerously low level. Further tempering causes the Izod value to improve so that when the steel is tempered to about 600°C., a relatively tough material is obtained. Secondly, I should like to ask Dr. Hatfield's opinion about the Bessemer process for making steel.

Dr. Hatfield has not referred to it this evening, and it appears to be going out of general use. I should be glad if Dr. Hatfield would give us the reason for this. Thirdly, will Dr. Hatfield say something about rim steel ? What are its special properties ?

Dr. Hatfield : With regard to temper brittleness. I once gave a paper to the Institution of Mechanical Engineers many years ago, and you might look it up. The paper was on the mechanical properties of steel, with some reference to the question of brittleness. Now when you speak of temper brittleness you are not speaking of " brittleness," in the usual sense, Mr. Loxham. You are not talking of brittle steel, but merely of steel which under the impact test gives a low absorption of energy. When I gave my paper about fifteen years ago I thought someone would be sure to challenge me and ask what the author meant by brittleness, and I thought I would be prepared, so the next time I came to London I went to a second-hand bookshop and I said, " Have you a Dr. Johnson's Dictionary, please ? " The man behind the counter said, " I think I have," and he went away and came back with this treasured volume in his hands. I said, " How much is it ? " and amazing to relate—this is only fifteen years ago—he said " 2s. 6d." Of course I seized the book and paid him the half-crown and said, " How is it this book is so cheap ? " " Well, you know, as a matter of fact, many better dictionaries have come out since," he said. But I still have that Dr. Johnson's Dictionary and it has stood me in very good stead. When I gave the paper Professor Howe opened the discussion and he got up and said, " Well, Mr. Chairman, firstly I would like to ask the author what he means by brittleness ? " I said, " I think that if Professor Howe will refer to Dr. Johnson's Dictionary, which will be equally an authority to him as an American as to me, an Englishman, he will find that brittleness is described as " Aptness to break." Now that is a very good definition, " aptness to break," and I want just to submit to Mr. Loxham that a steel may have a low Izod value without having that characteristic, the aptness to break. Now I have said so much on the question of "brittleness" because I want to say now that I do not regard at all highly, and never have done, the data derived from the notched bar impact test. If you want to break a bit of iron what do you do ? You put a notch in it and then you can easily break it. That is what you do in the Izod impact test. You start the cracking and the Izod test simply indicates the amount of energy necessary to propagate the crack once it is formed. What you are really concerned to know is whether or not the material is in such a condition as will militate against the crack ever being formed in the first place.

You ask me then to explain temper brittleness. Perhaps you won't require an explanation now I have reduced it to such low terms.

If you persist I find it difficult to say more than, as everyone knows, that although you may have a nickel-chromium steel with an impact stress of 120 tons in a hard condition with 20 foot-pounds. Izod value, if you take it and expose it to a temperature of 400 or 500° for a long time, you will still retain its tensile strength and its ductility, but you can drop its Izod value to as little as 5 foot-pounds. But now here is the interesting point. If you take that steel in the same tensile condition but with a high impact and a low impact strength, and you start with 10 mm. impact test pieces and you break them you get a great disparity in the Izod values. But if you go on increasing the size of those test pieces the disparity disappears. There are difficulties in explaining such a phenomenon. I cannot explain it. Many attempts have been made to explain it. All I can tell you is that breaking a notched piece of steel indicates the energy to be absorbed in breaking the steel, and I do not know any other field to which that factor can be referred. And that, I am afraid, is all I can tell you about it.

Now to come to the next point the Bessemer process. You asked me what I think of the Bessemer process. You mentioned that you thought it was dying out. Well it has nearly died out. There are one or two optimists who are trying to re-introduce it at the present time for specific purposes. I think that the works at Corby, which have been put down to produce steel of the rimming type such as was imported from the Continent, will be a success. But it should be realised that the manufacture of Bessemer steel—by virtue of the fact that you blow air through it in the molten state—is never under such quantitative scientific control as the open-hearth and electric processes; and unless it is on purely economic grounds, where it will gain an advantage, I do not think its resuscitation will be permanent, except for such specific purposes as the one mentioned.

The next point is—what is rimming steel ? Now, I wish I had known that that question was to be asked, because we have examined quite a number of rimming steel ingots. We have made a study of rimming steel on behalf of British Manufacturers. Now you remember the section that I put on the screen of an aero steel ingot. It was a homogeneous plane. Now if you section a rimming steel ingot, and take a sulphur print you have a most amazing result. You have anything from 1 to 5 or 6 in. of metal that does not affect the sulphur print at all all round the ingot and along the bottom as well, then inside is a zone of great impurity. It is clear that such material is of use only for sheets for motor car bodies and such duties where the impure centre is of no consequence.

A MEMBER : I have a problem allied to Mr. Loxham's temper brittleness. We have a number of pieces to case harden, 3%, 5%, nickel, and it is essential that the thread on the end of these shafts

should be kept soft. It is more economical to leave on a certain amount and turn the carbon off, so we opened with a patent cement cover with clay to keep it soft. Well, although you are very careful and you rely on your hardeners to be careful, the carbon does get on to the cement, and the tops of the threads, being very thin, get hard. So finding that brittleness was caused through the carbon content, we thought the easiest way out in order to keep that soft would be just to blow a flame on the thread, and we did that, sent them up to the straightening shaft to be straightened, and they pushed the ends off. Then we throught we would put them in a lead bath, and as a matter of fact we are still carrying on with that, but now and again we do push those threads off, and if the pinion is broken in half through the carbon section which has got to be left hard, and then the thread end is broken off and the breakage is viewed by the viewer you will find that the part that is broken through the carbon is quite a good section and its tensile is good, but the thread end is very poor throughout. I know it is caused probably through having different heat treatments, but I do not know how we can help ourselves.

Dr. Hatfield : I agree with you what you have done in your line of attack, but there is a selected temperature which I think would make you all right. Instead of me answering the question, however, would you care to send me one of these parts ? If you will I shall be pleased to examine it and give you a critical statement as to what you procedure should be. In principle you are on the right lines.

Member : You think the lead bath is right ?

Dr. Hatfield : Yes, but the lead bath may be subject to a certain variation in temperature. Do you know with accuracy exactly what temperature you are using in the bath ? You see with molten lead you can so easily super-heat it. Have you a pyrometer ? If you will send me to Sheffield, to the Brown-Firth Research Laboratories, a part subjected to this treatment I will have a very careful examination made, and I will give you what I really think is the best procedure to follow. It would be unwise for me to say any more without knowing more of the case in detail.

Mr. Ferguson : May I ask Dr. Hatfield one question, and that is if he can help us in clearing up a little difficulty we are confronted with ? In the butt welding of plates for cylindrical pressure vessels to Class I Lloyd's requirements it has been noticed that when examining the macro sections across the weld, fine laminated marks appear in the heat affected zone of the plate adjacent to the weld, and these defects are apparently due to sulphur segregations in patches which appear along the edges of the plate. The chemical-sulphur analysis

which arrives with this boiler plate is merely an average analysis and does not necessarily show up the concentration of sulphur or phosphorous in the segregated patches. Inasmuch as these macro sections are made after the vessel is entirely completed, X-rayed and heat treated, the risk of rejection of the vessel is enormously important. Is there any method of examination of the plate beforehand which would bring to light imperfections of this nature in the plate ?

DR. HATFIELD : I have already indicated this evening how these segregations of impurities appear scattered through the steel ingot, and if rimmed steel ingots were used there would be a greater likelihood of experiencing the trouble Mr. Fergusson has mentioned, and I would suggest that he warn the mills against the making of plate from rimmed ingots. The only way in which these sulphur segregations could be brought to light on the plate itself after rolling, would be to grind and polish the surface and take a sulphur print, which of course, would be too expensive and therefore impracticable.

MR. T. W. MILLER : I have been very interested in the discussion on free cutting steel to-night, because I have come against the problem myself very frequently. The firm I work with used to use a terrific quantity of the stuff, because they were concerned with machining a large number of small parts, $\frac{1}{2}$ in. or under, as quickly as possible, and we used the BSS. 32. Grade 4, as the standard specification : but we have all realised that we cannot use this grade of steel for heavier work.

When we got on to heavier work, especially case-hardened, we had to drop down on the sulphur and try the phosphorus to about .6—I do not know exactly—and we still found one important thing, namely that the quality given by the manufacturers was not uniform machining quality. We are not so much concerned about top speeds, now, because some of the machines, especially the older ones, won't take the speeds at which the steel is capable of handling, but if we want to get further down and have the standard grades of steel clean in the sense that Dr. Hatfield indicated, we find this difficulty, the machining speed is no longer uniform, and that is much more serious than the speed being low. We can adjust the machines for running at a low speed, 100 ft. per minute, according to the job in hand, but it is not uniform, and the non-uniformity of machining steel is much more serious to us than the lower speed. Is there a grade of steel available with a uniform speed ?

The other question I wanted to ask was this : some years ago there was a paper published by the Woolwich people, in which they said they had come up against the trouble with the carbon drilling rifle barrels in a moderately high carbon steel, and they reckoned

that if they managed to get the micro-structure of the barrel formed of thin lines of segregates, very narrow lines fairly closely placed together, you could take a straight drill through and you could make that drill very easily, provided the micro-structure was not spotty and irregular, but consisted of long parallel lines. Is there anything in mild steel, because frankly with regard to the formation of micro-structures, I have never found mild steel failing in that category. It is evidently due to the fact that the quantity of segregates is not enough to give this final steel condition.

Dr. Hatfield: I am very interested in your remarks. The experience of your company has confirmed what I have said about segregations, but I am not in a position to say that with a mild steel you will not get a uniform cutting steel within the limits that you have in mind. You are evidently dealing with a specific engineering problem, and in the case of rifle barrels you really have to work in a manner to suit yourself. I should be somewhat surprised if you got the results you need with mild steel. When you are talking of mild steel I presume you refer to normalized steel. It is not hardened and tempered?

Mr. Miller: Cold drawn.

Dr. Hatfield: Cold drawn? That makes it even worse. When the steel is cold drawn, the surface becomes work-hardened to a degree which depends upon the exact amount of reduction. It will be clear that serious differences in hardness—and consequent machineability—may be introduced in this way.

There is one further point, however. You are no doubt trying to machine this steel, are you not, with ordinary high speed steel? That is rather like the aborigines carving out their canoes with another piece of wood. In late years we have developed hard carbides, tungsten carbides, and so on, and I would submit to you that if you cannot tackle this matter from the standpoint of the material you might well find a solution by using a carbide tool. Have you tried one?

Mr. Miller: No, I do not think so.

Dr. Hatfield: With regard to rifle barrels, you have very accurately described the problems and the difficulty in drawing the barrels. We at the works make large quantities of rifle steel, and we specialize in getting the grain in a correct flow and proper crystal state to prevent it taking of the tool out of direction.

Mr. J. O. Johnston: Dr. Hatfield mentioned just now the proper size of crystal. I remember reading a year or so ago an article in an American magazine on grain size, and manufacturers were said to be offering steel with a guaranteed grain size. I would like Dr. Hatfield to tell me something about that.

DR. HATFIELD : That in itself is a very big subject. Different steels having different characteristics resulting from different compositions and different treatments are produced, and each has a natural grain size peculiar to itself. Well, it has become fashionable, and the movement came from America, to call for a specific grain size quite regardless of other factors—a small grain size— and that small grain size is achieved by putting aluminium into the steel. Addition of aluminium causes the dispersion throughout the steel of tiny inclusions of alumina which in turn form millions of nuclei for the growth of crystals. That is what happens, and if you want steel of a uniform small crystal you have only to say so and aluminium is put into the steel.

May I recall to you what I said a out the non-metallic inclusions—their adverse effect in the steel ? If you test steel which has been dosed in the aluminium in this way across the direction of rolling, you will find that the mechanical strength has been reduced. This shows you how very necessary it is that all the implications should be put before you in a matter of that character. You can have small grain sizes if you want to, but at a cost.

MR. N. V. KIPPING (Section President) proposed a cordial vote of thanks to Dr. Hatfield.